arXiv:astro-ph/9611124v1 15 Nov 1996

HI Observations of two Molecular Clouds with Extremely Large Velocity Dispersions

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Abstract

We have mapped two molecular clouds at $(\ell, b) = (3.2°, +0.3°)$ and $(\ell, b) = (5.4°, -0.5°)$ in 21-cm line and continuum emission. These clouds show unusually large velocity dispersions of more than 100 $\mathrm{km\,s^{-1}}$ (FWHM) which has also been seen in ^{12}CO, ^{13}CO, and CS emissions. This dispersion is roughly an order of magnitude larger compared to giant molecular clouds. From our HI observation we estimate that the atomic mass of the cloud at $\ell = 3.2°$ is about $1.5 \times 10^5\,\mathrm{M_\odot}$ and the mass of the cloud at $\ell = 5.4°$ is $7 \times 10^4\,\mathrm{M_\odot}$. The ratio of total molecular mass to atomic mass for these clouds appears to be normal for clouds near the galactic center. The main peculiar feature of these clouds is their abnormally large velocity dispersion; the extent in velocity is from about 0 km $\mathrm{s^{-1}}$ (LSR) to 200 km $\mathrm{s^{-1}}$. These clouds are connected, in the ℓ–v plane, to high velocity ridges that extend over several degrees of the longitude. These properties, we believe, provide important clues to the physical process responsible for their large velocity dispersion.

1 Introduction

There are more than 100 giant molecular clouds in the Galaxy with mass of 10^6 $M_\odot$ or greater. The internal velocity dispersion of these clouds, measured using ^{12}CO emission, is in most cases approximately equal to their virial velocity of about 15 km s^{-1} (Dame *et al.* 1986). However, there are at least two very unusual molecular clouds, located at (ℓ, b) =(3.2°, 0.3°) and (5.4°, −0.5°), which have extremely large velocity dispersions of about 100 km s^{-1} (FWHM) as seen in several molecular lines including ^{12}CO. Hereafter we shall refer to these objects as wide line clouds (WLCs). Oort drew attention to the large velocity dispersion of the WLC at 3.2° longitude in his influential review article almost two decades ago (1977). However, these clouds remained largely unexplored until the mid-eighties when Stark and Bania (1986) and Bitran (1987) mapped them at high spatial resolution in ^{12}CO, ^{13}CO, and CS, and confirmed their unusually large velocity dispersion. The observed velocity dispersion even in CS, which is associated with high density cores of clouds, is about 40 km s^{-1} compared to 5–10 km s^{-1} for giant molecular clouds. Both clouds are also visible in the large-scale OH absorption-line survey of Boyce and Cohen (1994a) where the properties of seven WLCs are discussed in the longitude range $354° < \ell < 6°$. For an overall ℓ–b map of this galactic centre region see Boyce and Cohen (1994b). In addition, the same authors have mapped the cloud at $\ell = 5.4°$ using H_2CO measurements and give a mass estimate of 5×10^6 $M_\odot$ (Boyce *et al.* 1989).

According to Bitran (1987) and Stark and Bania (1986) the mass of the clouds, estimated from the ^{12}CO emission, is about 10^7 $M_\odot$, however, this is very uncertain because the ratio of H_2 mass to CO emission for clouds in the inner few kpc is likely to be different from the solar neighborhood (Stacy *et al.* 1988). We have mapped the two WLCs in 21-cm in order to provide a lower limit to their mass, to determine their velocity dispersion, and to ascertain if they are different from giant molecular clouds.

In the next section we describe the observational details, Sect. 3 contains the results and a comparison with the CO-observations. The main results are summarized in Sect. 4.

2 Observations

We have observed the two wide-line clouds in 21-cm with the Effelsberg 100 m telescope using a cooled HEMT receiver with a system temperature less than about 30 K on cold sky but increased to about 55 K due to radio emission from the galactic centre and spillover from the ground. The total bandwith of the receiver was 3.12 MHz around the neutral hydrogen hyperfine transition frequency of 1420.4 MHz; the corresponding velocity range was −229.7 to 429.3 km s^{-1}. Using the 1024 channel autocorrelation spectrometer a resolution of about 1.3 km s^{-1} was obtained after Hanning filtering of the spectra. The clouds have been mapped in steps of 4.5′ which is half the beam width of the telescope. The total angular coverage in ℓ and b for the two clouds were (2.675°, −0.450°)–(3.725°, 0.975°)

and (4.875°, −1.250°)–(5.925°, 0.175°), respectively. Thus each cloud was scanned at 300 observation points with an integration time of 15 s per position. The temperature was calibrated by periodically switching to a stabilized noise tube, and the calibration of the noise tube was done by observing the standard area S7 before and after mapping each cloud. The resulting temperature calibration factors are used to convert the measured voltage to brightness temperature including atmospheric extinction. For both clouds the rms noise level in the raw data was about 700 mK. We did not however correct the maps for effects from the antenna side lobes; the resulting error is expected to be small (the relative sensitivity of the first side lobes, separated from the main beam by $14'$, is about 1%).

At low velocities the observed spectra are dominated by strong emission from foreground material. The WLCs can be seen as broad emission structures extending up to $V_{LSR} \approx 200$ km s^{-1}. At both ends of the observed velocity interval no neutral hydrogen emission was detected, and we have used these emission free regions to subtract a linear baseline from each spectrum with a baseline error of about 0.3 K.

3 Results and Discussion

In Fig. 1 we show average 21-cm spectra of the clouds, i.e. the brightness temperature averaged over the observed area. For the WLC at $\ell = 3.2°$ this average contains three distinct peaks. The first one at $V_{LSR} \approx 90$ km s^{-1} is caused by the emission from the WLC itself, the second one at $V_{LSR} \approx 165$ km s^{-1} is partly from the WLC and also contains a strong contribution from an arm-like structure at $b \approx 0.5$ which extends over the entire observed ℓ-range (compare Fig. 2). The high velocity peak at $V_{LSR} \approx 220$ km s^{-1} is entirely due to HI near the galactic center unrelated to the WLC.

In the composite HI spectra of the WLC at $\ell \approx 5.4°$ (fig. 1) two peaks can be seen. The one at $V_{LSR} \approx 85$ km s^{-1} is probably unrelated to the WLC. The strong peak at $V_{LSR} \approx 185$ km s^{-1} is again due to a extended arm-like structure which is however more uniformly distributed over the observed area with a strong contribution from emission at $b \approx -1°$. This WLC is weaker than the WLC at $\ell = 3.2°$ and is harder to recognize in the average spectrum.

Fig. 2 shows ℓ-v-maps for both of the observed regions. The WLCs are clearly seen and appear to cover a large velocity range of more than 100 km s^{-1}. It is a remarkable fact that in both cases the clouds end at high velocity ridges extending over the entire observed longitude range. These ridges can also be identified in the corresponding CO-maps, although the ratio of intensities between the clouds and the ridges are much larger in CO compared to HI, i.e. the ridges appear much weaker in CO.

Contour maps of the temperature integrated over the velocity range from 50 km s^{-1} to 200 km s^{-1} as a function of ℓ and b are shown in Fig. 3 for both WLCs in 21-cm as well as ^{12}CO emission. Both WLCs clearly stand out against the background, and their positions, sizes, and orientations obtained in HI coincide with the ^{12}CO emission; it is evident that we are looking at the same objects in both of these lines. There is a small offset of about

2 arcmin between the centers of the HI- and the ^{12}CO-map for the WLC at $\ell = 3.2°$. This is however insignificant since the shift is much less than the beam width for both observations. It can also be seen that the WLC at $\ell = 5.4°$ is partly obscured by the HI-emission from the galactic plane but stands out more strongly in ^{12}CO.

The WLCs are almost certainly not nearby objects. The reason for this is that the observed velocity range of the WLCs seen in 21-cm, as well as ^{12}CO, is approximately 0–200 km s^{-1}, with a mean velocity of about 100 km s^{-1}. Thus if these clouds were nearby objects on roughly circular orbit, then their orbital velocity projected along the line of sight would be small and therefore their observed internal random velocity should have comparable negative and positive values. This is contrary to the observations. The observed velocity of an object, on a circular orbit, in the galactic plane at longitude ℓ is

$$V_{LSR} = r_\odot[\Omega(r) - \Omega(r_\odot)] \sin \ell$$

where $r_\odot$ and r are the distances of the observer and the object from the galactic center, respectively, and Ω is the angular rotation speed. Taking $r\Omega$ to be approximately constant we find the distance of the WLC at $\ell = 3.2°$ from the galactic center to be $r_\odot/10$, and the one at $\ell = 5.4°$ to be $r_\odot/6.4$. Thus the distance d of the WLCs from us is approximately $r_\odot$.

The total neutral hydrogen mass of the WLCs is estimated from the observed flux in 21-cm using the formula

$$\frac{M_{\rm HI}}{M_\odot} = 3.213 \times 10^2 \left(\frac{d}{8.5 \text{ kpc}}\right)^2 \int d\ell\, db\, dv\; T(\ell, b, v) \ , \qquad (1)$$

where T is brightness temperature in K, v is the velocity in km s^{-1}, and ℓ and b are measured in degrees. This expression follows from the number of hydrogen atoms along the line of sight as given by Burton (1988) multiplied with the atomic hydrogen mass and the suface element $dA = d^2 \cos b\, d\ell\, db \approx d^2\, d\ell\, db$.

Substituting the observed quantities in the above equation we find that the HI mass in the cloud regions, i.e. without subtracting any background emission, are about 3×10^5 M$_\odot$ for the $\ell = 3.2°$ cloud, and 10^5 M$_\odot$ for the cloud at $\ell = 5.4°$. These values were obtained by integrating the brightness temperature over the velocity range of 50–200 km s^{-1} in order to eliminate most of emission from foreground HI. However, there is a substantial 21-cm emission in this velocity range associated with the galactic plane at the angular location of both of the WLCs that must also be subtracted in order to determine the atomic mass of these clouds. We have tried several different ways of estimating this *background* emission. One method is to calculate the total HI emission outside the region occupied by each cloud, and multiply it by the fractional area covered by the cloud to yield the contribution of the background emission. This procedure gives the *corrected* HI mass of the WLC at 3.2° to be 8×10^4 M$_\odot$, and the WLC at 5.4° to be about 3×10^4 M$_\odot$. However, this method overestimates the *background* contribution, or underestimates cloud mass, since the emission from outside the cloud region is very nonuniform and is dominated by the strong 21-cm emission

from the galactic plane. We have also subtracted average spectra from the cloud region before calculating the mass from the integral of equation (1); various areas outside the clouds were used to determine the average spectra. When the galactic plane is not included in the area that is used in estimating the average spectra, then we obtain cloud mass that are approximately the averages of the two extreme values mentioned above, and is likely to be closer to the actual atomic mass of these clouds which lie outside of the galactic plane. Our best estimate of the HI mass of the WLC at 3.2° is $1.5 \times 10^5 M_\odot$, and the WLC at 5.4° is $7 \times 10^4 M_\odot$ with an uncertainty of about a factor of 2.

The HI mass is obviously the lower limit to the total cloud mass, most of which is molecular hydrogen. Neutral hydrogen in a typical giant molecular clouds is observed in a halo surrounding the cloud, with a ratio of HI to molecular mass of roughly 10% (e.g. Anderson, Wannier & Morris 1991, Elmegreen & Elmegreen 1987). The neutral hydrogen mass of the WLCs is about 1% of their total mass as determined from the ^{12}CO emission (Bitran 1987). It has been suggested that the ratio of H_2 mass to ^{12}CO emission for clouds near the galactic center is perhaps smaller by a factor of about 10 compared to the value in the solar neighborhood (see Stacy *et al.* 1988). We also expect to see a larger fraction of the ^{12}CO molecules in these clouds because of their large velocity dispersion. Taking these factors into consideration we conclude that the ratio of the HI mass to the total mass for the WLCs is not very different from giant molecular clouds.

4 Summary

We have mapped two molecular clouds at $\ell = 3.2°$ and $\ell = 5.4°$ in the 21-cm line emission of neutral hydrogen. These clouds show unusually large velocity dispersions of more than 100 km s^{-1} (FWHM) which has also been seen in lines of ^{12}CO, ^{13}CO, and CS. The position, size, and orientation of both of the wide line clouds (WLCs) are the same in HI and ^{12}CO maps. The WLCs are very prominent features in the ℓ-v-maps and show up as highly extended vertical bands.

These clouds lie about 0.3° from the Galactic plane and are almost certainly within about 1 kpc of the Galactic center. The mass of the clouds calculated from their ^{12}CO emission, using the standard ratio of H_2 to ^{12}CO mass, is about 10^7 M$_\odot$ (Bitran 1987); however for clouds in the Galactic center region the ratio of H_2 mass to ^{12}CO luminosity is perhaps smaller by a factor of about 10 compared to the value in the solar neighborhood. From our HI observation we estimate the atomic mass of the WLCs at $\ell = 3.2°$ and 5.4° to be 1.5×10^5 M$_\odot$, and 7×10^4 M$_\odot$ respectively, with an uncertainty of about a factor of 2 due to the error in the determination of the background emission. The ratio of HI to molecular mass of the WLCs does not appear to be abnormal for clouds near the Galactic center, provided we use the ratio of H_2 to ^{12}CO preferred for this region.

It is striking that the WLCs extend in velocity from roughly 0 km s^{-1} (LSR) to about 200 km s^{-1}. Moreover, both of these clouds appear to end at high velocity ridges, in the ℓ–v plane, that are very bright in 21-cm and

extend over the entire observed longitude range (Fig. 2).

These ridges are also visible in ^{12}CO maps extending to several degrees in longitude; however the ridges are much less prominent in CO compared to HI. Boyce and Cohen (1994a) have found similar structures (which they call filaments) in their OH absorption-line measurements, and these filaments seem to connect several of the seven WLCs described in this survey. We believe that these features provide important constraints to the physical origin of the enormous velocity dispersion of the WLCs.

Acknowledgment: PK is grateful to Pat Thaddeus for suggesting this problem, numerous discussions and the use of his CO data. We are indebted to Tom Dame for many interesting discussions about molecular clouds and for suggesting several improvements to the presentation of our work. This work was carried out while PK was visiting the Institute for Advanced Study, Princeton. He is very grateful to John Bahcall for his comments, support and hospitality.

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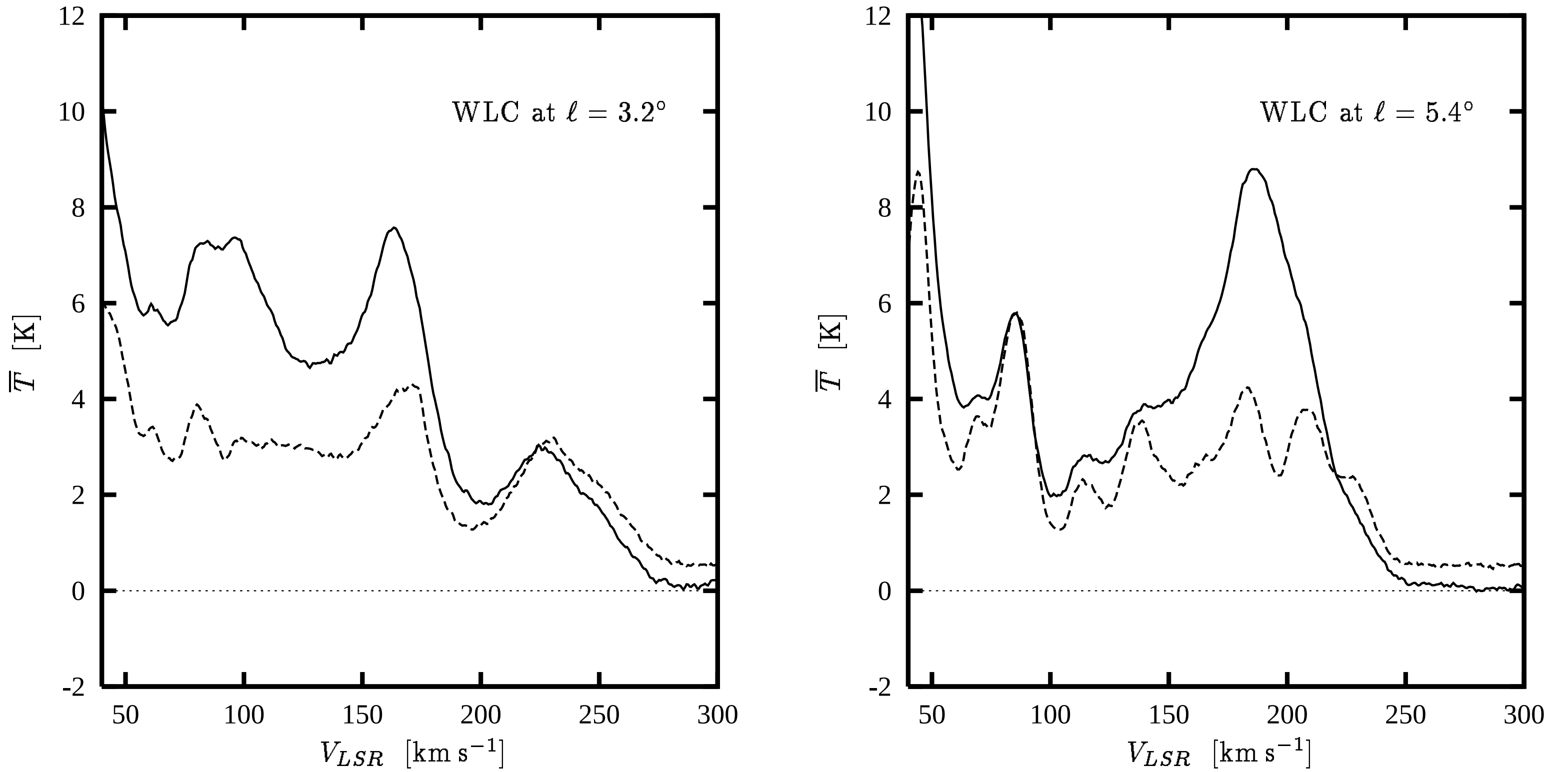
Figure Captions

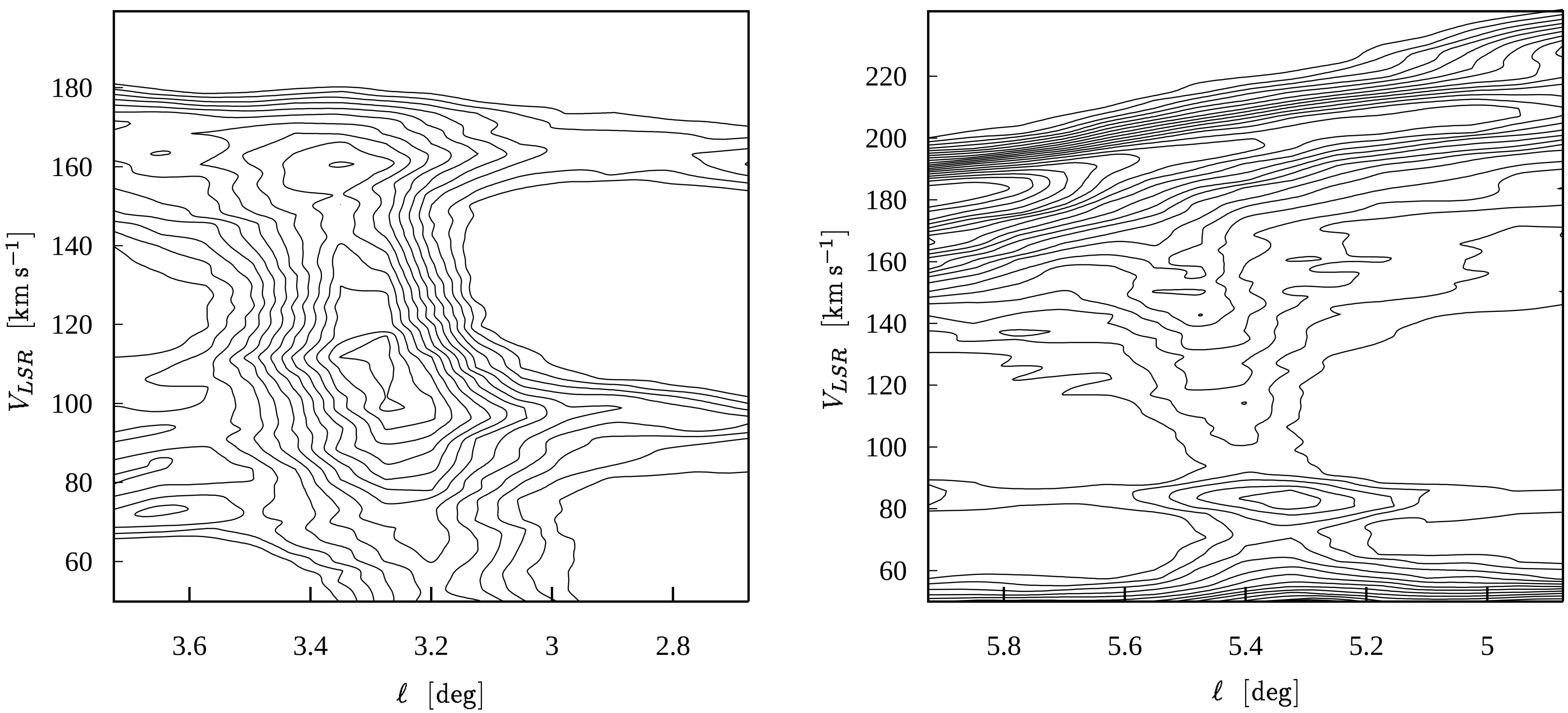
Fig. 1. – Composite HI spectra of the WLCs as a function of velocity. The solid lines show the brightness temperature averaged over the entire observed area. The dashed lines are the corresponding variances. The left/right panels are for clouds at $\ell = 3.2^\circ/5.4^\circ$

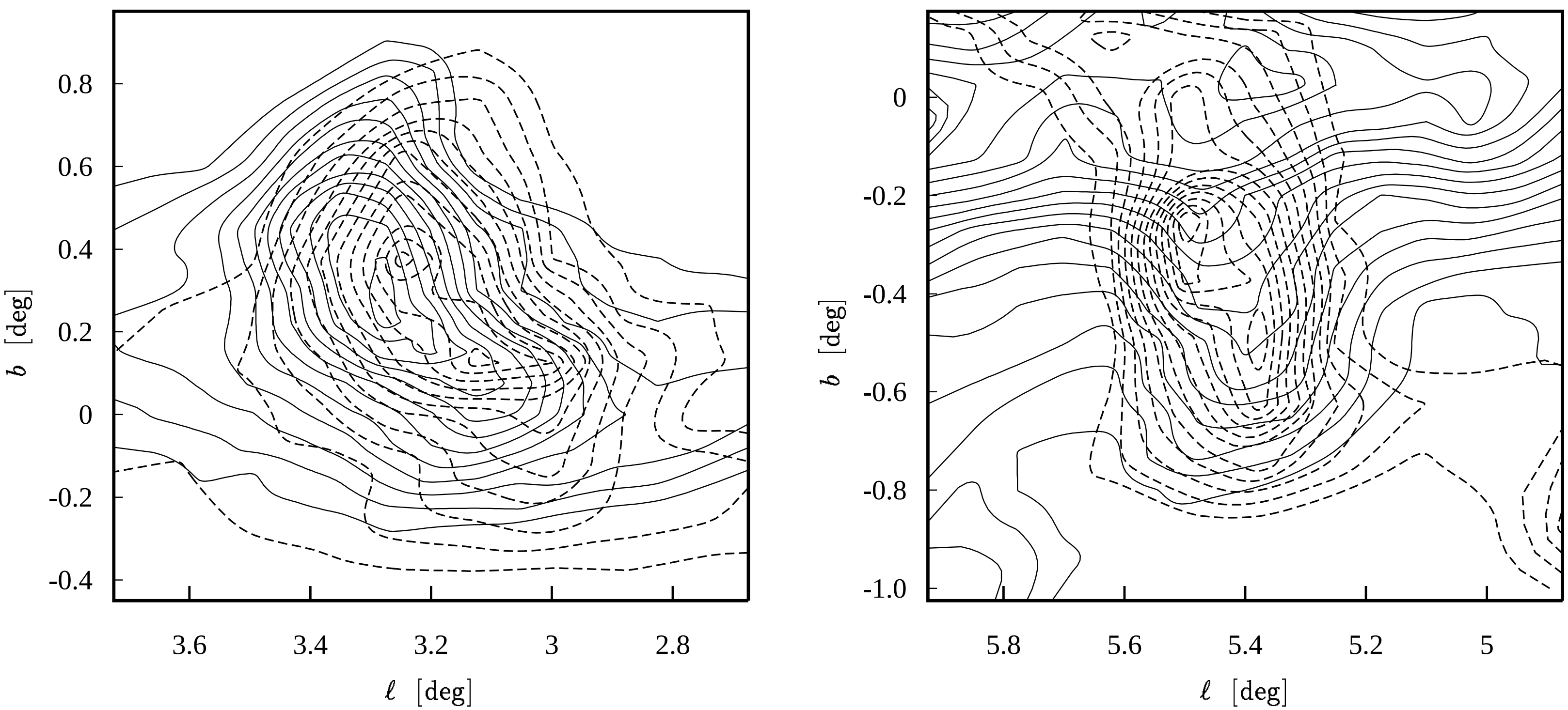
Fig. 2. – Longitude-velocity contour maps of both WLCs. The maps show the brightness temperature integrated over the b-range $(0.15^\circ,\ 1.0^\circ)$ for the cloud at $\ell = 3.2^\circ$, and over $(-1.0^\circ,\ -0.15^\circ)$ for the $\ell = 5.4^\circ$ cloud. Contour levels are separated by 0.5 K deg.

Fig. 3. – Longitude-latitude contour maps of both WLCs. The solid lines represent the HI data (brightness temperature), and the dashed lines show the ^{12}CO data (antenna temperature). Velocity integration ranges are $(50,\ 200)$ $\mathrm{km\,s^{-1}}$ and $(40,\ 240)$ $\mathrm{km\,s^{-1}}$ for the HI and ^{12}CO maps, respectively. No background subtraction has been performed for these maps. The corresponding contour levels are separated by 75 K $\mathrm{km\,s^{-1}}$ (HI) and 50 K $\mathrm{km\,s^{-1}}$ (^{12}CO) for the WLC at $\ell = 3.2^\circ$, and 50 K $\mathrm{km\,s^{-1}}$ (HI) and 20 K $\mathrm{km\,s^{-1}}$ (^{12}CO) for the $\ell = 5.4^\circ$ cloud. The ^{12}CO data is courtesy of P. Thaddeus & T. Dame, and was obtained using a 1.2 meter telescope; for details please see Dame et al. (1987) & Bitran (1987).



WLC at $\ell = 3.2°$
WLC at $\ell = 5.4°$
$\overline{T}$ [K]
V_{LSR} [km s^{-1}]
12
10
8
6
4
2
0
-2
50
100
150
200
250
300


180
160
140
120
100
80
60
V_{LSR} [km s^{-1}]
3.6
3.4
3.2
3
2.8
ℓ [deg]
220
200
180
160
140
120
100
80
60
V_{LSR} [km s^{-1}]
5.8
5.6
5.4
5.2
5
ℓ [deg]



0.8
0.6
0.4
0.2
0
-0.2
-0.4
b [deg]
3.6
3.4
3.2
3
2.8
ℓ [deg]
0
-0.2
-0.4
-0.6
-0.8
-1.0
b [deg]
5.8
5.6
5.4
5.2
5
ℓ [deg]